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Radiation from Waves Guided by Nonuniform Active Surfaces

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The concept of electronically manipulating the complex wave numbers of waves launched along guiding surfaces is intriguing and appropriate for this special session on new trends. Actually, these concepts were disclosed over 15 years ago [1,2]. In fact, they have even been patented [3], but these disclosures are rather obscure. Coupled with the fact that technology for designing and constructing nonuniform and active wave-guiding surfaces is not yet developed has precluded wide knowledge or acceptance of these concepts. Nevertheless, the concepts are still unique and worthy of re-examination within the realm of feasible but undeveloped ideas.

The concepts are based on being able to synthesize surfaces on which the surface impedance boundary condition, Z_s, can take on values anywhere in the complex plane. In particular, we hypothesize nonuniform surface impedances having a negative real part over some finite portion of the surface. With such a capability, one of several species of guided waves can be propagated at a time, and then converted to another species as the wave propagates from one zone to the next having a different Z_s. Consider, for example, the 2-D problem where the normalized nonuniform surface impedance $\Delta(x) = Z_s(x)/\eta_o$ is symmetrical about the z-axis in the interval $-L<x<+L$ as shown in Fig. 1. For $|x| > L$, we take $Z_s = 0$. Free space exists for $y > 0$. Let M_1 be a uniform z-directed line source of strength K_1 situated at (0,h) and M_2 be a source of strength K_2 located at the test point (x_0,y_0). The boundary condition $\mathbf{y} \times \mathbf{E}' = -Z_s \mathbf{H}'$ is assumed to apply over the entire surface. The integral formulation is obtained from the electro-magnetic compensation theorem, wherein the solution for H'_{1z} is given in terms of the known fields, H_{1z} and H_{2z} of both sources when the entire $y = 0$ surface is perfectly conducting.

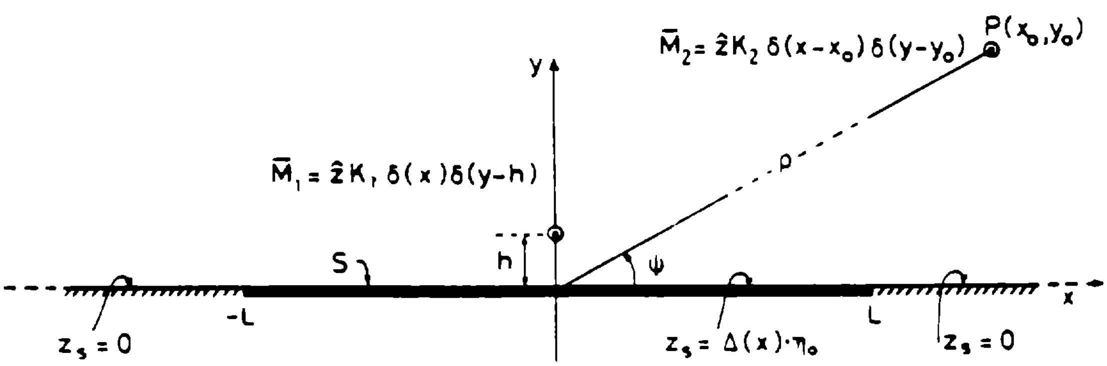

Fig. 1. Geometry for a magnetic line source over a smooth but nonuniform surface impedance plane.

[1] Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

$$H'_{1z}(x_0,y_0) = H_{1z}(x_0,y_0) + \frac{\eta_o}{K_2}\int_{-L}^{+L} \Delta\,(x)H'_{1z}(x,0)H_{2z}(x,0)dx \qquad (1)$$

Within the hypothesis that $\Delta(x)$ can be specified, this solution is exact and fully accounts for all effects of the nonuniform $\Delta(x)$, including reflections from any discontinuities. Details and numerical procedures are given in [4,5] as applied to nonuniform passive surfaces.

Guidelines for predicting the field on the surface and the radiation pattern are needed to specify interesting or potentially useful profiles of $\Delta(x)$. This can be done using guided wave antenna theory for piecewise uniform surfaces. Equivalent results are simply obtained by investigating the behavior of the well known Sommerfeld attenuation function $F(p)$, which is the solution of (1) when Δ is constant everywhere. In separated form,

$$H'_{1z}(x,o) = H_{1z}(x,o)F(p) \quad (2) \quad \text{where} \quad p = \frac{-jkx}{2}\,|\Delta|^2\, e^{j2\phi} \quad (3)$$

with $\phi = \arg \Delta$. Of particular interest here is the behavior of $F(p)$ when $\pi/4 < \phi < 5\pi/4$. The first term of the asymptotic expansion is [1,6]

$$F(p) \;\cong 2(\pi\,|p|)^{1/2}\, e^{-j3\pi/4} e^{j|p|\cos 2\phi} e^{-|p|\sin 2\phi} \qquad (4)$$

from which it is a simple matter to deduce the behavior of $F(p)$ depending upon the angular sector in which ϕ lies, as shown in Fig. 2.

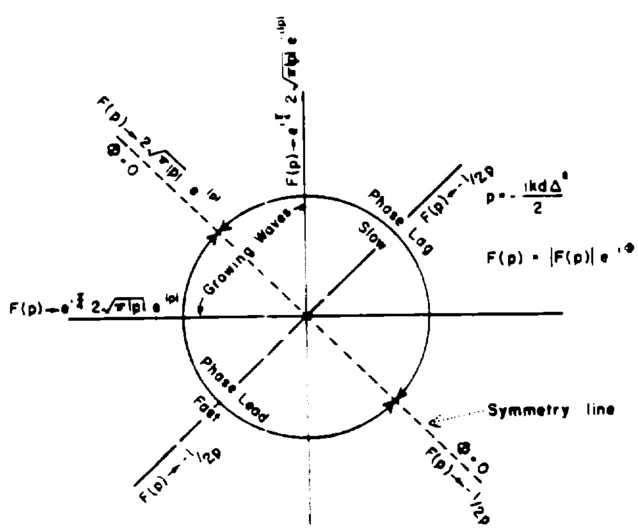

Fig. 2. Complex Δ $(=Z_s/\eta_o)$ plane showing asymptotic behavior of $F(p) = |F(p)|e^{j\varnothing(p)}$.

Of course, the field on the surface cannot grow indefinitely in the second quadrant, and so zones on the plane having these properties must be of finite length. Although $F(p)$ pertains to a constant impedance plane, it is known that a guided wave propagating over a nonuniform surface impedance very rapidly acquires the attenuation and phase rate of change corresponding to the local value of Δ. This permits us to apply (4) to piecewise uniform surfaces to determine the local phase and attention constants. From this we find that the approximate local angle of radiation is

$$\psi \cong \cos^{-1}\left[1 - \frac{\mathrm{Re}(\Delta^2)}{2}\right] \tag{5}$$

while the attenuation over a piecewise uniform section is $|\delta P|\sin 2\phi$, where $|\delta P|$ is the change in numerical distance over the section.

A number of cases were numerically studied using (1) and the preceding guidelines to specify the impedance profiles. One of the most interesting cases is shown in Figs. 3 and 4. The line source $\mathbf{M}_1$ was situated at $h = 0.195\lambda_o$ over a purely inductive surface of $\Delta = j0.5$ for $0 < |x| < \lambda_o$, giving a near maximum surface wave launching efficiency [4,5]. This is followed by a smooth transition region where ϕ varies essentially linearly from $\pi/2$ to $3\pi/4$. At this point the wave begins to grow and radiate. In the range $1.65 < x/\lambda_o < 6$, the wave is amplified 23dB by causing ϕ to vary linearly in the range $3\pi/4 < \phi < \pi$. All the while, the radiation angle ψ is fixed at 26° by holding $\mathrm{Re}(\Delta^2) = .2$. For $6 < x/\lambda_o < 14$, ϕ moves into the domain $\pi < \phi < 5\pi/4$ where the wave radiates, still at $\psi = 26°$ by holding $\mathrm{Re}(\Delta^2) = ..2$, but is damped to a negligible value at the end of the active surface. Thus, over the entire range $1.65 < x/\lambda_o < 14$, the impedance is made to vary in such a manner that the wave initially grows 23dB, then decays 37dB to a negligible value, all the while radiating at $\psi \simeq 26°$ according to (5).

The radiation pattern for this impedance profile as computed using the exact relation (1) is shown in Fig. 4. The actual angle of peak radiation is 29.5°, compared to the approximate angle $\psi = 26°$ predicted by (5).

The synthesis of such nonuniform active surfaces is largely an open question. Ultimately, it is desirable that $\Delta(x)$ be electronically controllable, enabling controlled scanning and beam shaping. Some suggestions are given to possible realizations and applications.

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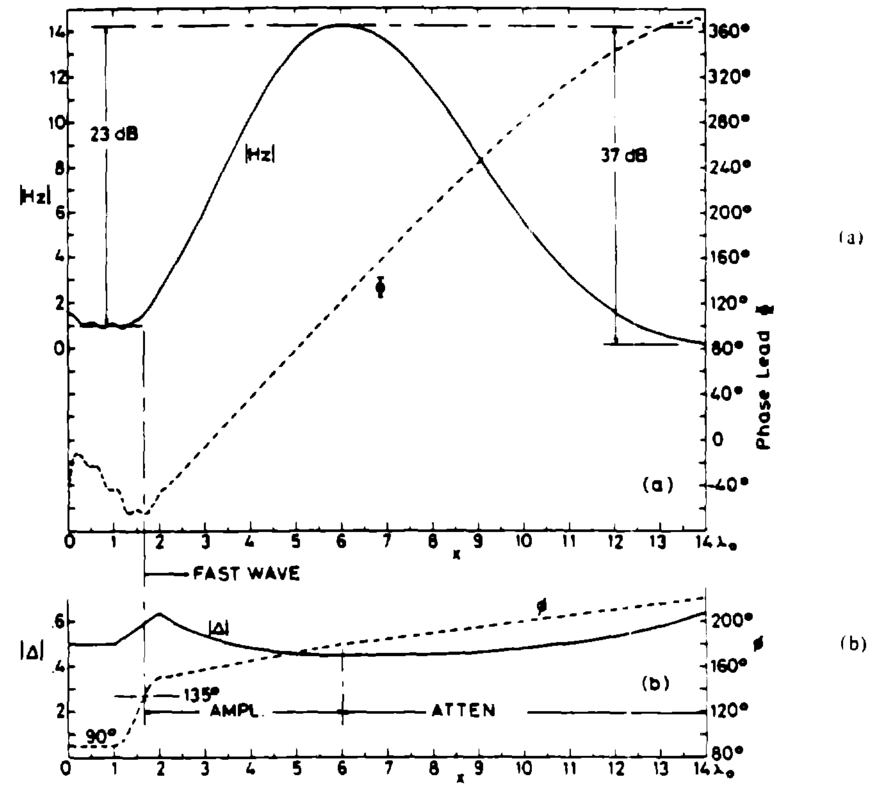

Fig. 3. (a) Magnitude and phase lead of H_z on the surface of a $14\lambda_0$ long active traveling wave antenna. The corresponding surface impedance profile is shown in (b) and the radiation pattern is shown in Figure 4.

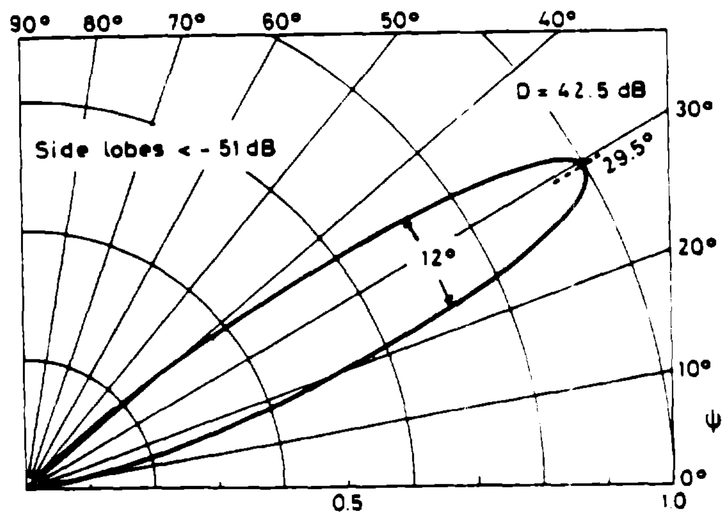

Fig. 4. Radiation pattern for the surface impedance profile shown in Fig. 3(b).